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Department of Environmental Engineering

PhD Thesis
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Preface

The work presented in the present PhD thesis was conducted at the Department of Environmental Engineering of the Technical University of Denmark, from September 2012 to January 2016. The work was conducted under the supervision of Associate Professor Charlotte Scheutz and Senior Researcher Jacob Møller and was generously founded by the 3R PhD School.

During the PhD study four scientific papers as listed below were produced. Throughout the thesis the papers will be referred to by their Roman numerals I-IV.

I Naroznova, I., Møller, J., Scheutz, C. Characterization of biochemical methane potential (BMP) of individual material fractions of source-separated organic household waste in Denmark. Submitted to Waste Management. November 12, 2015.

II Naroznova, I., Møller, J., Larsen, B., Scheutz, C. Evaluation of a new pulping technology for pre-treating source-separated organic household waste prior to anaerobic digestion. Waste Management. Accepted with revisions. December 9, 2015.

III Naroznova, I., Møller, J., Scheutz, C. Life cycle assessment (LCA) of the global warming potential of anaerobic digestion versus the incineration of individual material fractions in Danish source-separated organic household waste. Submitted to Waste Management. December 23, 2015.

IV Carlsson, M., Naroznova, I., Møller, J., Scheutz, C., Lagerkvist, A. (2015). Importance of food waste pre-treatment efficiency for global warming potential in life cycle assessment of anaerobic digestion systems. Resources, Conservation and Recycling, 102, 58-66. DOI 10.1016/j.resconrec.2015.06.012

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from: DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

In addition, the following publications were made (albeit not included in the present thesis):

Naroznova, I., Møller, J., Scheutz, C. (2015). Energy recovery from garden waste in a LCA perspective. In S. Scalbi, A. Fominici Loprieno, & P. Sposato (Eds.), International conference on Life Cycle Assessment as reference methodology for assessing supply chains and supporting global sustainability challenges : LCA for 'feeding the planet and energy for life'. (pp. 198-201). Roma: ENEA.

Møller, J., Naroznova, I., Scheutz, C., Foged Larsen, B., Peter Jensen, J. (2015). Fremstilling af et højværdisubstrat til biogasproduktion ved sampulpning af have/parkaffald og kildesorteret organisk dagrenovation vha. Ecogiteknologien. København K: Miljøstyrelsen.

Naroznova, I., Møller, J., Scheutz, C. (2013). Life Cycle Assessment of pretreatment technologies for anaerobic digestion of source-separated organic household waste. In Proceedings Sardinia 2013. CISA Publisher.

Naroznova, I., Møller, J., Scheutz, C. (2013). Life Cycle Assessment: Ecogi vs. Screw press: Technical report for Vestforbrænding I/S. Kgs. Lyngby: DTU Environment.

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This PhD thesis was conducted under the supervision of Associate Professor Charlotte Scheutz and the co-supervision of Senior Researcher Jacob Møller, both of whom I wish to thank first. They provided me with the full toolbox to complete this thesis successfully, by providing invaluable knowledge, enthusiasm and support, not only for the thesis, but also for many personal aspects. I appreciate your greatly and will never forget what you did for me.

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Great thanks are extended to Hector Hernan Caro Garcia, Hector Osvaldo Ampuero Diaz and Sinh Hy Nguyen, the latter of whom offered significant support in the laboratory: thank you, especially as, on occasion, the thought of going into the lab without knowing you would be there filled me with horror!

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At this point, I would like to thank my family, friends and all of the people who stood by my side during the three-and-a-half years it took to complete my PhD. I will not list your names here; I will just take the chance to thank our Lord Jesus Christ for having you all in my life.

I have applied for the PhD thesis position at DTU Environment on the strong advice of Lorie Hamelin, from University of Southern Denmark, and would never have come up with this idea without her input. My PhD life has seen a number of up and downs, but now that the story is coming to an end, I can truly say thank you, dear Lorie, for your advice and your belief in me. My PhD topic turned out to be not only about organic waste, it was also about my life in general and therefore incredibly important to study.

I also extend my gratitude to the 3R PhD School for their financial support of this project.

Summary

Driven by the Waste Management Directive and the Renewable Energy Directive, the biological treatment of organic household waste, such as food waste from kitchens, now needs to be undertaken by European Union member countries. Anaerobic digestion (AD), which allows for the utilisation of both energy (biogas production) and nutrients (through the agricultural use of digestion residue) is commonly suggested as the best way forward in this regard. The common practice of acquiring organic waste from other waste involves introducing sorting guidelines to citizens, with the corresponding material fractions included in these procedures, followed by the separate collection of source-separated organic household waste (SSOHW).

A main topic related to the implementation of this scheme on a large scale is feedstock characterisation. This is important for system optimisation regarding both technical performance, e.g. by predicting methane production and the amount of residue, and also the environmental profile, e.g. by assessing the environmental value of impact contributions when substituting fossil energy and mineral fertilisers. SSOHW is known as a highly heterogeneous waste stream, and thus its characterisation is not an easy task.

SSOHW is also accompanied by non-biodegradable impurities in the collected waste fractions. This issue is usually addressed through the physical pre-treatment of SSOHW, at which stage it is desirable to reject the maximum amount of non-biodegradable impurities while minimising biodegradable matter loss. Several well-established technologies, each with its own advantages and disadvantages, are known, and these sit alongside newly emerging solutions.

To ensure the environmental sustainability of the waste management sector when implementing the AD of SSOHW, it is important that the process has a better environmental profile than the alternative treatment being displaced, in this case incineration. When comparing AD to incineration, climate change effects indicated by global warming potential (GWP) from a life cycle assessment (LCA) perspective can be used as criteria.

The overall aim of this PhD study is to provide background data for the environmental assessment of a wide range of AD of SSOHW implementations in Europe. To achieve this aim, three specific objectives were formulated regarding waste characterisation, physical pre-treatment and European framework conditions:

- Characterise individual material fractions present in Danish SSOHW pertinent to their biochemical methane potential and other parameters of importance for AD treatment.
- Describe the technologies currently available for the physical pre-treatment of SSOHW prior to AD in Scandinavian countries, and provide the necessary data required to include them in LCA SSOHW management models.
- Determine the framework conditions that will ensure the best AD of SSOHW performance when considering climate change.

Waste characterisations for all EU member states, as well as descriptions of all available pre-treatment technologies, were not possible to detail within the scope of the present PhD thesis. Therefore, waste characterisation was limited to Denmark, and only Scandinavian pre-treatment technologies were included, but it is assumed that the data, to some extent, can be used to describe more general European conditions if country-specific data are unavailable.

Regarding the first objective, hand-sorting of SSOHW in a Danish municipality (where the source separation of organic household waste has been implemented) was performed, desirable material fractions sampled and a range of laboratory investigations performed. The material fractions covered were: animal food waste (AFW), vegetable food waste (VF), kitchen tissue (KT), vegetation waste (VW), moulded fibres (MF), animal straw (AS), dirty paper (DP) and dirty cardboard (DC).

For the second objective, a thorough assessment of a new pre-treatment technology in Denmark was followed by making a comparison to alternative pre-treatment technologies in Scandinavian countries. For the technology assessment, the material flow analysis principle was used, in that the technology process was described and LCA inventory data were generated. Amongst existing pre-treatment technologies, the screw press-, disc screen- and dispersion-based processes were represented by data from the literature.

The last objective was addressed through two LCA studies. The first assessed climate change effects associated with the AD of SSOHW compared to incineration, by concentrating on individual material fractions, and the second assessed the climate change effects of optimising the AD of SSOHW at the pre-treatment stage of the life cycle.

Based on this work, the following results were achieved:

- Using the GWP criterion only one material fraction – VFW – was always better for AD compared to incineration. For AFW, KT, VW and DP, performance with AD was better unless it was compared to a highly efficient incinerator. Material fractions such as MF and DC were attractive for AD, albeit only when AD with CHP and incineration with mainly heat production were compared. AS was always better to incinerate.
- In Denmark, food waste (both animal- and vegetable-derived) and kitchen tissue were the main material fractions allowing GWP mitigation with AD when it was compared to incineration, while the inclusion of other material fractions with SSOHW sorting guidelines was of less importance.
- The new pre-treatment technology introduced in the present thesis is a promising solution for pre-treating SSOHW prior to AD, and it had advantages over the screw press-, disc screen- and dispersion-based pre-treatment technologies.
- Any change in pre-treatment efficiency, such as ± 10% material recovered from the biomass, does not affect the net GWP of the AD of SSOHW significantly, meaning that other aspects, e.g. economy, practicality or other environmental aspects of relevance, might be used as guidance when selecting the technology for practical use.

Dansk sammenfatning

Drevet af affaldshåndteringsdirektivet samt direktivet om vedvarende energi, vil biologisk behandling af organisk husholdningsaffald, såsom madaffald fra køkkener nu blive udført inden for EU-landene. Som behandlingsmetode foreslås bl.a. bioforgasning, der giver mulighed for udnyttelse af både energi (ved biogasproduktion) og næringsstoffer (ved landbrugets anvendelse af afgasset biomasse). Den almindelige praksis for at opnå fraktionen af organisk affald udsorteret fra andet affald indebærer indføring af sorteringsretningslinjer for borgerne med de relevante materialefraktioner inkluderet efterfulgt af separat indsamling af kildesorteret organisk dagrenovation (KOD).

Et meget vigtigt emne relateret til implementering af bioforgasning af KOD i stor skala er karakterisering af substratet. Dette er vigtigt for optimering af teknisk ydeevne, f.eks. til at forudsige produktionen af metan og mængden af afgasset biomasse, og også til at bestemme miljøprofilen, f.eks. ved at vurdere den miljømæssige værdi af bidrag fra substitution af fossil energi og mineralsk gødning. KOD er kendt som en yderst heterogen affaldsstrøm og dermed er dens karakterisering ikke en let opgave.

KOD indeholder nogle ikke-biologisk nedbrydelige urenheder i de indsamlede affaldsfraktioner. Dette bliver normalt adresseret gennem fysisk forbehandling af KOD, hvor man ønsker fjernelse af en maksimal mængde ikke-bionedbrydelige urenheder samtidig med at tabet af bionedbrydeligt materiale minimeres. Flere veletablerede teknologier, hver forbundet med fordele og ulemper, er kendte, men også nye løsninger dukker op.

For at sikre miljømæssig bæredygtighed i sektoren for affaldshåndtering ved bioforgasning af KOD er det vigtigt, at bioforgasning af KOD har en bedre miljøprofil end den alternative behandling herunder forbrænding. Til sammenligning af bioforgasning med forbrænding kan virkningerne af klimaændringer, angivet som det globale opvarmningspotentiale (GWP) i et livscyklusvurderingsperspektiv, anvendes som et kriterium.

Det overordnede formål med dette ph.d.-studie var at levere baggrundsdata for en miljømæssig vurdering af gennemførelsen af bioforgasning af KOD i Europa. For at gøre dette blev tre specifikke mål formuleret med hensyn til affaldskarakterisering, fysisk forbehandling og europæiske rammebetingelser:

- Karakterisering af individuelle materialefraktioner tilstede i dansk KOD vedrørende deres biokemiske metanpotentiale og andre parametre af betydning for behandling med bioforgasning.
- Beskrivelse af teknologier til fysisk forbehandling af KOD til bioforgasning, der er tilgængelige i de skandinaviske lande og give de nødvendige oplysninger til at inkludere dem i LCA-modeller vedrørende behandling af KOD.
- Bestemmelse af rammebetingelser, der sikrer den bedste miljøprofil af bioforgasning af KOD vedrørende klimaændringer.

Affaldskarakterisering, som inkluderede alle EU-lande, samt beskrivelse af alle tilgængelige forbehandlingsteknologier var ikke muligt inden for rammerne af den foreliggende ph.d.-afhandling. Derfor blev affaldskarakterisering begrænset til Danmark, og kun skandinaviske forbehandlingsteknologier blev medtaget, men det antages, at de genererede data til en vis grad kan bruges til at beskrive mere generelle europæiske forhold, hvis landespecifikke data er ikke tilgængelige.

Med hensyn til det første specifikke mål blev KOD fra en dansk kommune (hvor kildesortering af organisk dagrenovation er implementeret) håndsorteret, der blev taget prøver af de relevante materialefraktioner, og en række laboratorieundersøgelser blev udført. Materialefraktionerne inkluderede: animalsk madaffald (AFW), vegetabilsk madaffald (VFW), køkkenrullepapir (KT), vegetationsaffald (VW), støbte papfibre, herunder toiletruller og æggebakker (MF), halm fra kæledyr (AS), snavset papir (DP) og snavset pap (DC).

For at opfylde det andet specifikke mål blev der udført en grundig vurdering af en ny forbehandlingsteknologi i Danmark efterfulgt af en sammenligning med de alternative forbehandlingsteknologier, som eksisterer i de skandinaviske lande. I forbindelse med teknologivurderingen blev der anvendt principper fra materiale-flow analyse, hvorved teknologiprocessen blev beskrevet, og der blev genereret LCA inventory data.. Blandt de eksisterende forbehandlingsteknologier blev skruepresse-, disk screen- og dispersion-baserede processer repræsenteret vha. litteraturdata.

Det sidste specifikke mål blev behandlet i to LCA studier. Det første vurderede potentielle klimaændringer ved bioforgasning af KOD i forhold til forbrænding med enkelte materialefraktioner i fokus, og det andet studie vurderede potentielle klimaændringer ved at optimere bioforgasning af KOD i forbehandlingsfasen af livscyklussen.

Baseret på det udførte arbejde opnåedes følgende resultater:

- Ved brug af GWP kriteriet var der kun én materiale fraktion - VFW - som altid var bedre ved bioforgasning sammenlignet med forbrænding. For AFW, KT, VW og DP, var ydeevnen bedre med bioforgasning, medmindre den blev sammenlignet med et meget effektiv forbrændingsanlæg. Materialefraktioner som MF og DC var kun attraktive for bioforgasning under rammebetingelser, hvor bioforgasning med kraftvarme og forbrænding med hovedsageligt varmeproduktion blev sammenlignet. AS var altid bedst at forbrænde.

- I Danmark er madaffald (både kød og vegetabilsk) og køkkenaftørringspapir de vigtigste materialefraktioner, som medfører nedsat GWP ved bioforgasning i forhold til forbrænding, mens inddragelse af andre materialefraktioner vha. KOD sorteringsvejledninger er af mindre betydning.

- Den nye forbehandlingsteknologi undersøgt i nærværende afhandling er en lovende løsning til forbehandling af KOD før bioforgasning og har fordele i forhold til skruepresse, disk screen og dispersion-baserede forbehandlingsteknologier.

- Ændring af forbehandlingseffektivitet med ± 10% med hensyn til materiale genvundet i biomassen påvirker ikke netto drivhuseffekten ved bioforgasning af KOD ret meget, hvilket betyder, at andre aspekter, f.eks. økonomi, funktionalitet, eller andre miljømæssige aspekter af relevans kan anvendes til at afgøre valg af teknologi for praktiske anvendelse.

Table of contents

Abbreviations

AD	Anaerobic digestion
BMP	Biochemical methane potential
EU	European Union
GWP	Global warming potential
LCA	Life cycle assessment
MFA	Material flow analysis
SSOHW	Source-separated organic household waste
TBMP	Theoretical biochemical methane potential
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

1 Introduction

1.1 Background and motivation

In light of increased industrialisation and resource consumption, organic waste management solutions have been recognised as an important way to secure sustainable performance. For biodegradable waste (e.g. food waste, green waste), the efficient use of both materials and energy is required. This, in turn, can be realised only by anaerobic digestion (AD) treatment, which allows for the utilisation of energy, through biogas production, and nutrients, through the agricultural use of digestion residue (Christensen, 2011). Another biological treatment option – composting – aims at recovering nutrients only, and, furthermore, it is associated with considerable environmental loads at the process stage (Bernstad and la Cour Jansen, 2011). Two-stage treatment with AD and composting combined can also be applied. In these cases, it is suggested that the AD process should be initiated first (Hartmann and Ahring, 2006).

Driven by the two Waste Management and Renewable Energy Directives (European Parliament, 2008; European Parliament, 2009), the AD of source-separated organic household waste (SSOHW) may become a part of national waste management strategies in the European Union (EU). In some member countries (e.g. Austria and Germany), source-separation of organic household waste, followed by biological treatment, has been applied successfully since the 1990s (Ministry for a Liveable Austria, 2015; European Compost Networks, 2015). However, many European countries have still not implemented source separation, and so organic waste is either landfilled or incinerated. The topic is thus highly relevant today, especially because of the current focus at EU level.

An important topic related to implementing the AD of SSOHW on a wide scale is feedstock characterisation, in order to optimise the technology as well as predict methane production and the amount and quality of residue. SSOHW is generally characterised by high heterogeneity, which makes direct measurements a difficult task, and so pre-treated samples are more commonly investigated (Davidsson et al. 2007; Hansen et al., 2007b; Bernstad et al., 2013). The characteristics of untreated SSOHW, however, may be obtained by characterising individual material fractions present in SSOHW composition; this approach is currently applied in EASETECH, which is a software package widely applied for life cycle assessment in waste management and was developed by the Technical University of Denmark (Clavreul et al., 2014). Among the feedstock properties commonly monitored for AD, biochemical methane potential (BMP) is a major requirement (Lesteur et al., 2010; Angelidaki et al., 2009). To evaluate material appropriateness for treatment in AD, biodegradability is evaluated, which normally involves establishing material composition for different organic components like proteins, lipids and carbohydrates (Moeller et al., 2004; Triolo et al., 2011). For fibre-rich materials (e.g. paper waste, vegetation waste), the content of lignocellulose biofibres, which are complex structures in plant materials and are mainly comprised of lignin, hemicellulose and cellulose, is of concern (Teghammar et al., 2010; Triolo et al., 2011).

In practice, the AD of SSOHW is normally accompanied by physical pre-treatment, which aims at improving collected organic waste quality by removing non-biodegradable impurities and also making it “pumpable” (Bernstad et al., 2013; Hansen et al., 2007a). A general requirement for pre-treatment technologies is to reject non-biodegradable impurities while ensuring minimum biodegradable matter loss during impurity rejection. Thus, the performance of the pre-treatment technology affects energy recovery and material recovery from SSOHW and also produces biomass quality – all of which, in turn, are essential aspects in assuring overall benefits from the AD of SSOHW, both economically and environmentally. Life cycle assessment (LCA) is an important support tool for decision making regarding SSOHW management. To reflect the SSOHW life cycle properly, inventory data regarding pre-treatment technologies are required.

To ensure environmental sustainability of the waste management sector, it is important that the AD of SSOHW has a better environmental profile than the treatment being displaced. In order to choose the most efficient waste treatment option for resource and energy utilisation, global warming potential (GWP) is a common criterion. The GWP profile of the AD of SSOHW compared to the alternative of landfilling organic household waste (without source separation), for instance, is vastly superior (Finnveden et al., 2005). In contrast, for the AD of SSOHW versus organic household waste incineration, which is an essential alternative for organic household waste treatment in Europe (suitable for energy recovery), cases when the incineration GWP profile is better are known (Bernstad and la Cour Jansen, 2011; Fruergaard and Astrup, 2011).

1.2 Research objectives

The overall aim of this PhD study is to provide background data for the environmental assessment of a wide range of AD of SSOHW implementations in Europe. To achieve this aim, three specific objectives were formulated for waste characterisation, physical pre-treatment and European framework conditions:

- Characterise individual material fractions present in Danish SSOHW pertinent to their biochemical methane potential and other parameters of importance for AD treatment.
- Describe the technologies currently available for the physical pre-treatment of SSOHW prior to AD in Scandinavian countries, and provide the necessary data required to include them in LCA SSOHW management models.
- Determine the framework conditions that will ensure the best AD of SSOHW performance when considering climate change.

The three objectives above were addressed in the three first scientific papers included in the present thesis (**Paper I**, **Paper II** and **Paper III**, respectively). In relation to the second and third objectives, **Paper IV** was also developed.

The thesis is structured in six sections (sections 2-6) as follows. In section 2, methods used throughout the project are presented. In sections 3, 4 and 5, the main aspects associated with each of the three objectives are detailed, and in section 6, the conclusions are made and future work is outlined.

2 Methods

The approach applied to achieve the research objectives was based on a combination of a number of methods, which may be summarised as follows: 1) waste sampling and characterisation, 2) material flow analysis (MFA), 3) life cycle assessment (LCA) and 4) literature review. In the four following sections, the principles behind each method, as well as its application through the project, are described.

2.1 Waste sampling and characterisation

Waste sampling and characterisation were performed to obtain data for the biochemical methane potential (BMP) and other parameters for individual material fractions found in Danish SSOHW (**Paper I**). The method involved fieldwork aimed at retrieving the samples (hand-sorting of SSOHW collected from a Danish municipality where source separation of organic household waste has been implemented) and was followed by a range of laboratory investigations. The waste was collected from 83 single-family households during two weeks in November during 2013. To obtain reliable samples for the laboratory investigation, sample size reduction was performed (see detailed in **Paper I**). Moreover, an assortment of sample preparation techniques were applied, namely freezing waste samples down with liquid nitrogen, particle size reduction with a cutter mill and, in some cases, drying and shredding. To get representative subsamples for the analyses, a riffle splitter was applied. The characterisation work included determining BMP and material composition for protein content, lipids, volatile fatty acids (VFA), lignocellulose biofibres and easily degradable carbohydrates. For the lignocellulose biofibres, lignin, hemicellulose and cellulose fractions were differentiated. Moreover, standard parameters for total solids (TS) and volatile solids (VS) content were determined. Using analytical results, theoretical BMP (TBMP), overall material degradability (BMP divided by TBMP) and the degradability of lignocellulose biofibres (defined as the degradable share of VS of lignocellulose biofibres) were calculated. Investigations into BMP and the content of TS and VS were also performed for the degradable biomass samples involved in the research in **Paper II**. Details on all of these analytical techniques (including the calculation approaches) can be found in the respective papers.

2.2 Material flow analysis

Material flow analysis (MFA) can be utilised when mass flows in a range of different systems need to be characterised, and it is based on the "principle of mass conservation," whereby an input into the system equals output plus stock (Brunner and Rechberger, 2004). In general, the two main MFA steps can be distinguished: (1) data collection and (2) data processing. For data collection, the main issue is to ensure data reliability, as data sources may be diverse: literature data, laboratory investigations, etc. Through data processing, an MFA system is built based on the collected data, normally by applying one of the available MFA software-based tools, e.g. STAN 2.5 (STAN, 2012).

Within the present PhD thesis, the MFA principle was used for assessing a new technology for SSOHW pre-treatment (**Paper II**). The assessment was built on full-scale trials treating three SSOHW batches, whilst the data for main mass flows related to technology operation, e.g. generated waste flows, water flows, as well as electricity consumption, were collected. For some of the waste flows, physiochemical analyses of TS and VS contents, and the content of hazardous substances and nutrients, were performed; moreover, composition as the relative distribution of particular material fractions and particle size was determined. Data collection in the fieldwork was carried out by the respective papers' co-author Bjarne Larsen, but it was hampered by many practical issues regarding accessibility to the mass flows at the pre-treatment facility. The PhD student's task was to process the data into an MFA system that required supplementing the analytical dataset with external data (see details within **Paper II**). For data processing, the mass flow analysis tool STAN 2.5 was used. As a result, an MFA for technology related to the treatment of 1 tonne of SSOHW (wet weight), including a fresh water inlet and electricity consumption, was created. In addition, material transfer on the substance level with regards to hazardous substances and nutrients, and transfer for specific material fractions in the input SSOHW, were established.

2.3 Life cycle assessment

Life cycle assessment (LCA) is a standardised methodology used as a support tool within the field of environmental engineering (ISO, 2006a; ISO, 2006b). The method involves examining the environmental impacts of a product or service throughout its entire life cycle (often determined as "from cradle to grave"), by classifying them into particular impact categories (e.g. global warming, terrestrial acidification). The standard LCA methodology includes four steps as follows: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA) and (4) result interpretation. Within the goal and scope, a research objective and system boundaries are defined. With LCI, input data for each life cycle stage are collected, e.g. environmental emissions, resource consumptions. The results of the LCI are then classified further into selected impact categories by expressing them in particular units, e.g. CO_2 eq. for global warming. These are characterised results of LCIA. The characterised impacts can be further normalised by expressing them in a common person equivalent (PE) unit, known as the normalisation step of an LCIA, and weighted considering weight of each impact category among others (normally, political decision-based), known as the LCIA weighting step. These normalisation and weighting steps, however, are optional. At this point, a number of LCIA methods can be used, e.g. EDIP97 (Wenzel et al., 1997), ILCD2011 recommended (European Commission, 2011), etc. For the last LCA step – result interpretation – the obtained results are interpreted and discussed from the perspective of the goal and scope introduced at the beginning of the research. With this method, two LCA approaches are differentiated: consequential and attributional, whereby, for the former system, expansion and marginal LCI data are modelled, while for the last system allocation and average LCI data are used.

Within the present thesis, LCA was applied to our investigations, as reflected in **Paper III** and **Paper IV**. In both cases, a consequential LCA approach was used. The modelling was performed using EASETECH software and included the use of LCI, both from the model database and developed purposefully for the projects. The LCIA was carried out based on the ILCD2011 recommended methodology and included an evaluation of midpoint environmental effects for climate change (global warming potential, GWP) with a 100-year time horizon. For the final outcomes, characterised results were used and conclusions for the research question were conducted.

2.4 Literature review

The research question in **Paper I**, on the characterisation of individual material fractions in Danish SSOHW, was also associated with a literature data review. The review was dedicated to determining the status of the data sought in the framework of the study (see **section 2.1**), in order to conclude on the need for dedicated laboratory investigations. The review involved a search for data in international scientific articles and reports. In particular, BMP and other characterisation data related to waste treatment with AD were included in the search, e.g. content of total solids (TS), volatile solids (VS), organic components (proteins, lipids, carbohydrates and VFA), carbon (C), hydrogen (H), oxygen (O), nitrogen (N)-content, which alternatively could be applied to estimate the TBMP of material fractions, as well as material degradability. The data for individual material fractions comprising SSOHW were the main focus of this exercise. However, during the search, data for SSOHW in general (untreated as well as after any type of pre-treatment) were also considered. Data on single food waste products (e.g. banana peel) were, in the meantime, disregarded. As a result of the review, a dataset compiled from seven studies (all that were available) was established (can be observed within **Paper I**). The review was followed by a critical assessment of the collected data so that the respective conclusion could be drawn. Consequently, the collected data were found to be insufficient for properly answering the research question in the study, meaning that the laboratory investigations were found to be relevant.

3 Characterisation of SSOHW for AD

3.1 Sorting guidelines and fractional composition of average SSOHW in Denmark

The most usual way of obtaining SSOHW involves introducing SSOHW sorting guidelines to citizens, with the corresponding material fraction details included, followed by separate collection of the generated biomass (Davidsson et al., 2007; Bernstad and la Cour Jansen, 2012). As introduced in **Paper I**, variations in SSOHW sorting guidelines are possible. When SSOHW for AD is in focus, material fractions which may degrade in anaerobic conditions might be sorted.

SSOHW sorting guidelines commonly applied in Denmark include material fractions such as food waste of both animal and vegetable origin, some small vegetation waste, like flower buckets and pot plant parts, in-house pet bedding (e.g. straw, also including excrement), kitchen tissue paper and alike and paper waste products made from moulded fibres (e.g. egg trays and kitchen tissue or toilet paper rolls). In other EU member countries, similar material fractions are included in SSOHW sorting guidelines. However, the sorting of materials rich in fibres (e.g. vegetation and paper waste) is not always the case. (Particular examples of SSOHW sorting guidelines in different EU member countries are given in **Paper I**).

In practice, sorting is rarely perfect, and so a proportion of materials not included in the sorting guidelines is early always found in the generated SSOHW. Basically, these impurities consist of different paper and cardboard products, plastics, glass and metals. When not suitable for the recycling (mainly due to contamination), paper and cardboard waste materials among the impurities, however, could also be accepted for SSOHW.

A detailed procedure aimed at determining the relative distribution of particular material fractions in waste was developed by Edjabou et al. (2015). For Danish SSOHW, respective investigations were performed by Petersen and Manokaran (2012). In **Table 1**, the fractional composition of average untreated SSOHW in Denmark, based on Petersen and Manokaran's (2012) results, is presented. It should be noted that in the original dataset (i.e. given by Petersen and Manokaran, 2012), the contribution of vegetable food waste, animal food waste, vegetation waste, moulded fibres and kitchen tissue is not specified; in the meantime, the contribution of "biowaste," standing for all of these material fractions together, is used. To specify the contribution of each fraction in particular, the relative weight of the corresponding material fractions in typical municipal solid waste in Denmark, as presented by Edjabou et al. (2015), was used. A multi-family house case was used. Material fractions in Edjabou et al. (2015) considered for each material fraction herein can be observed in **Paper III** (Table 3, the caption).

Table 1. Fractional composition of average SSOHW in Denmark. The table is from Paper I.

Material fraction	% wet weight
Vegetable food waste	58.9
Animal food waste	13.0
Vegetation waste	12.7
Moulded fibres	0.1
Kitchen towels	6.6
Animal straw	1.0
Diapers	0.8
Dirty cardboard	2.2
Dirty paper	0.8
Plastics	1.4
Glass	0.1
Metals	0.2
Other combustibles	2.2
Total:	100.0

3.2 Characterisation of individual material fractions in SSOHW

Material fractions commonly accepted for SSOHW can be allocated into two general waste types: (1) food waste and (2) fibre-rich waste. Food waste of animal and vegetable origin belongs to (1), while vegetation and paper waste might be attributed to (2). All of these material fractions are biodegradable, and in anaerobic conditions they will generate methane. Different material fractions, e.g. plastics, metals and glass, are non-biodegradable and therefore might be considered as “mis-sortings.”

For material fractions belonging to (2), the share of lignocellulose biofibres might be determined, which in turn concerns biochemical methane potential (BMP) and the overall biodegradability of these materials compared to food waste material fractions. Lignocellulose biofibres are complex structures in plant materials and are mainly comprised of lignin, hemicellulose and cellulose. As stated in Triolo et al. (2011), the low biodegradability of lignocellulose biofibres in AD reactors is due to lignin being non-degradable in anaerobic conditions, because cellulose and hemicellulose are tightly packed in the lignin and are therefore responsible for drastically reduced biodegradability (Jørgensen, 2009; Raju et al., 2010). With particular pre-treatment methods, a lignocellulose structure can, however, be destroyed – and thus biodegradability improved (Taherzadeh and Karimi, 2008).

3.2.1 Data available in the literature

The literature review performed within framework of the present PhD thesis (**Paper I**) revealed that characterisation data on individual material fractions in Danish SSOHW, as well as SSOHW in other countries, are scarce. The most comprehensive data setup characterises individual material fractions in SSOHW in Japan, as presented by Kobayashi et al. (2012). To apply these data for characterising Danish SSOHW, potential differences within material fractions should be considered.

3.2.2 Analytical results

In the present PhD thesis, eight biodegradable material fractions that could be distinguished in the composition of Danish SSOHW were investigated (**Paper I**). Material fractions covered by the investigation were: animal food waste (AFW), vegetable food waste (VF), kitchen tissue (KT), vegetation waste (VW), moulded fibres (MF), animal straw (AS), dirty paper (DP) and dirty cardboard (DC). A detailed description of waste materials associated with each fraction is given in the corresponding manuscript. The main results obtained are presented in **Table 2**. For the result interpretation, it should be noted that the samples used for the analyses represent material after use, e.g. KT is not clean kitchen tissue but kitchen tissue with food waste remaining on it and furthermore inter-contaminated because of placing them in a common waste bin. During the investigation, the following parameters are covered: content of total solids (TS), volatile solids (VS), proteins, lipids, cellulose, hemicellulose, lignin, easily-degradable carbohydrates, biochemical methane potential (BMP), theoretical BMP (TBMP) and material degradability (BMP as a percentage share of TBMP).

As evident from the results, the largest BMP (572 mL CH_4/g VS) and material degradability (98%) were achieved for animal food waste (AFW), which might be due to the significant content of lipids in material composition (25%

VS). The BMP and material degradability of the other food waste material fractions, i.e. vegetable food waste (VFW), were also pronounced (425 mL CH_4/g VS). Among fibre-rich material fractions, BMP and material degradability of kitchen tissue (KT) and dirty paper (DP) were the largest (419 and 372mL CH_4/g VS, respectively), which, as with AFW, might be due to a significant amount of lipids in the composition. Lipid content for the paper waste herein should, in turn, be caused by contamination with food waste, which is natural for this type of material. The lowest BMP (110 – 271mL CH_4/g VS), as well as material degradability (22 – 59%), was achieved with material fractions such as vegetation waste (VW), moulded fibres (MF), animal straw (AS) and dirty cardboard (DC), which might be related to the larger amounts of lignin in those materials.

For the composition of different organic compounds (i.e. proteins, lipids, etc.), the following was discovered. Carbohydrates (both lignocellulose biofibres and easily degradable carbohydrates) were the dominant compounds for all material fractions. Fibre-rich material fractions such as kitchen tissue (KT), moulded fibres (MF), animal straw (AS), dirty paper (DP) and dirty cardboard (DC) were rich in lignocellulose biofibres. In contrast, food waste materials (animal food waste (AFW) and vegetable food waste (VFW)) were rich in easily degradable carbohydrates. In vegetation waste, shares of lignocellulose biofibres and easily degradable carbohydrates were equally large. For all material fractions, the VFA contents were negligible at less than 0.1% VS (results are not shown).

A share of lignocellulose biofibres was assumed to be degraded when the BMP measured in the batch incubation test was larger than the TBMP calculated from proteins, lipids and easily degradable carbohydrates. This was observed for all of the material fractions except for vegetation waste (VW), for which no lignocellulose biofibres were degraded and incomplete degradation of some proteins, lipids and easily-degradable carbohydrates might have happened as well. In animal food waste (AFW), the entire share of cellulose and hemicellulose was degraded, and for material fractions such as kitchen tissue (KT), degradation was close to complete. For all other material fractions (moulded fibres (MF), animal straw (AS), dirty paper (DP) and dirty cardboard (DC)) non-degraded shares varied from 41 to 98%, with the lowest for AS indicating that pre-treatment of the corresponding material fractions may be relevant.

Table 2. Analytical results for eight material fractions of SSOHW investigated in the present study. Standard deviations are provided below each measured value. For all properties determined by measurements, i.e. TS, VS, content of protein, lipids, cellulose, hemicellulose, lignin and BMP, the standard deviation was calculated from replicate samples (triplicates for all except for lignocellulose biofibres, which were duplicates). For other properties, i.e. easily degradable carbohydrates, TBMP and material degradability, the standard deviation was estimated based on Gauss's law of error propagation for independent random variables (Peralta, 2012). The table is from Paper I.

					Lignocellulose biofibres						
	TS, % ww	VS, % TS	Protein, % VS	Lipids, % VS	Cellulose, % VS	Hemicellulose, % VS	Lignin, % VS	Easily-degradable carbohydrates, % VS	BMP, mL CH_4/g VS	TBMP, mL CH_4/g VS	Material degradability, % TBMP
Animal food waste (AFW)	41	84	12	25	2	7	2	52	572	582	98
	0.4	0.3	0.01	1.6	0.5	0.8	0.4	1.9	18	18	4
Vegetable food waste (VFW)	24	93	5	14	12	10	5	53	425	518	82
	0.5	0.1	0.2	0.2	0.2	0.3	0.6	0.7	11	6	2
Kitchen tissue (KT)	32	94	2	10	60	5	2	21	419	480	87
	0.1	0.4	0.1	0.2	0.1	0.3	0.3	0.5	14	4	3
Vegetation waste (VW)	27	89	5	7	22	10	13	43	237	504	47
	0.3	0.5	0.1	0.1	1.5	0.3	0.6	1.6	32	10	6
Moulded fibres (MF)	57	81	1	2	62	5	11	19	202	462	44
	0.3	0.3	0.01	0.1	0.5	1.5	0.2	1.6	3	10	1
Animal straw (AS)	52	94	3	2	42	16	20	18	110	491	22
	0.2	0.2	0.02	0.2	0.5	1.6	0.3	1.7	12	11	2
Dirty paper (DP)	54	91	1	12	61	3	3	19	372	498	75
	1.3	1.3	0.1	0.1	1.0	1.1	0.1	1.5	18	9	4
Dirty cardboard (DC)	86	83	1	3	65	7	7	17	271	457	59
	0.0	0.1	0.05	0.6	1.1	1.0	0.5	1.6	4	12	2

Based on the BMP results obtained for individual material fractions, the BMP for average SSOHW in Denmark composed as presented earlier within the present PhD thesis (see **Table 1**). For non-biodegradable material fractions (diapers, plastics, glass, metals and other combustibles present in SSOHW), the contribution to BMP was assumed to be zero. The VS content of diapers, plastic and other combustibles was approximated by their wet weight, while the other non-degradable material fractions, namely glass and metals, were assumed not to include any VS. Thus, the BMP of 104 m^3 CH_4 per tonne wet weight of SSOHW, corresponding to 404 mL CH_4 per g VS, was obtained. The BMP per tonne of wet weight for individual SSOHW material fractions could be also derived. For material fractions such as vegetable food waste (VFW), vegetation waste (VW), moulded fibres (MF) and animal straw (AS), the BMP values were lower than the average BMP per tonne wet weight of SSOHW, meaning that an increase in the relative content (per wet weight) of these material fractions in the waste would lead to an overall BMP decrease and thus might be less desirable if the goal is to maximise methane production per tonne of SSOHW. In contrast, four other SSOHW material fractions contributing to the BMP, i.e. animal food waste (AFW), kitchen tissue (KT), dirty paper (DP) and dirty cardboard (DC), did have higher individual BMPs per wet weight than the average SSOHW, which implies that an increase in the corresponding material weight in source-separated organic household waste will lead to an overall BMP increase and thereby higher methane production per tonne.

4 Description of the physical pre-treatment of SSOHW prior to AD and its modelling within LCA

4.1 Existing technologies in Scandinavian countries

In Scandinavian countries, the physical pre-treatment of SSOHW, based on a screw press or disc screen, is currently the most reliable and is thereby applied in most cases (Hansen et al., 2007a; Bernstad et al., 2013). A screw press is a device that squeezes waste through a metal sieve by applying pressure, while a disc screen is a technique for separating smaller, denser particles from larger, lighter objects by passing organic waste through rotating discs set at certain distances apart. Use of these techniques is associated with substantial losses of biodegradable materials to the reject – according to Hansen et al. (2007a) up to 40% and 35% (wet weight) for the screw press and disc screen, respectively. Moreover, the share of non-biodegradable materials, e.g. pieces of plastic bags used for waste collection, also of large particle size (as with the disc screen) may be substantial (Hansen et al., 2007a). Based on Bernstad et al.'s (2013) study, electricity consumption associated with screw press-based pre-treatment ranges from 9 to 28 kWh per tonne of SSOHW, while for the disc screen a range of 8-36 kWh per tonne of SSOHW is presented. A pre-treatment technique with fewer material losses to the reject (< than 20%, wet weight basis) exists in Sweden – the dispersion process presented in Bernstad et al. (2013). The technique is based on powerful milling equipment commonly used within the pulp and paper industry. The technique, however, is quite complex and is associated with high energy use (83.5 kWh per tonne of SSOHW treated). Furthermore, the dispersion process requires considerable amounts of water (1.1 m^3 per tonne of SSOHW treated in comparison to 0.6 m^3 reported for the screw press-based pre-treatment). As also presented by Bernstad et al. (2013), SSOHW pre-treatment with a screw press or a disc screen requires shredding or milling of the collected waste, and for the dispersion process bag-opening is required.

4.2 A new technology in Denmark

Due to increasing interest in optimising the pre-treatment of SSOHW prior to AD, new technologies and techniques are also emerging. One such pre-treatment technology was recently developed in Denmark. The new technology involves waste pulping with water running from a specially developed screw mechanism. The screw induces mechanical motion in the waste mass, which in turn results in dispersion (pulping) of the biodegradable materials (e.g. food waste, paper), without tearing the non-biodegradable (e.g. plastics materials into pieces. For the separation process, a perforated plate with a hole size of 6 mm is used. The two outputs from the system are biopulp (predominantly biodegradable solid biomass) and reject (mainly non-biodegradable impurities). The value of the biopulp for biogas production is related to its TS content, and the biopulp therefore has to meet certain TS content specifications. Unlike other pre-treatment technologies, the new technology accepts SSOHW as collected from households, i.e. in waste bags, with no pre-shredding or milling. The process, in the meantime, is associated with considerable water consumption. The optimisation work dedicated to this aspect, however, is considered. A detailed description of the technology design and performance can be found in **Paper II**.

Within the framework of the present PhD thesis, a detailed investigation into the new technology was performed (**Paper II**). As described within the method section, the investigation involved full-scale trials treating SSOHW collected from a Danish municipality and were followed by a range of laboratory analyses. Overall, the assessment included (1) the establishment of mass flows for the technology, including water consumption, (2) the determination of the quality of the produced biopulp, (3) the determination of the composition of the reject, including total content of biodegradable materials, (4) tracking the transfer of substances of concern through the system and, finally, (5) a comparison of the technology's performance with other pre-treatment alternatives.

Based on the results for (1), (2) and (3), it was concluded that the new technology performed in a way that was appropriate for the subsequent biopulp treatment in an AD plant, i.e. material distribution between the process outputs was mainly biodegradable matter (of sufficiently good quality) to the biopulp (84-99% of the total biodegradable material in the input SSOHW, TS basis) and non-biodegradable impurities to the reject (> than 95% of the total, wet weight basis). The average content of biodegradable materials in the reject was estimated at 16% (TS basis). About 18% of the TS and VS in the SSOHW were lost to the reject. On a wet weight basis, the rejected materials accounted for 9% of the SSOHW. Overall biopulp quality was determined as follows. The content of non-biodegradable TS contributed less than 1% of total TS in the biopulp, while contamination with particles larger than 1.3 mm was also low at 4.8% of total TS. The BMP of the biomass produced by the new technology was 469 mL CH_4/g VS. The electricity consumption of the new technology was 41 kWh per tonne of SSOHW treated, and water consumption was 1.21 m^3 per tonne SSOHW. It was also indicated that further system optimisation for clean water consumption through water recirculation may be considered.

Results for (4) showed that the vast majority of carbon (total), most of which was carbon (biogenic), nitrogen (N) and phosphorus (P), was transferred to the biomass, namely 85, 88 and 92% (of the amounts in untreated SSOHW) for carbon (total), N and P, respectively. For heavy metals, transfer from the SSOHW to the biopulp varied depending on the individual substance, and it was highest for Hg and lowest for Pb and Cr.

Results for (5) are highlighted in **section 4.3** in the present thesis.

4.3 New technology versus existing alternatives

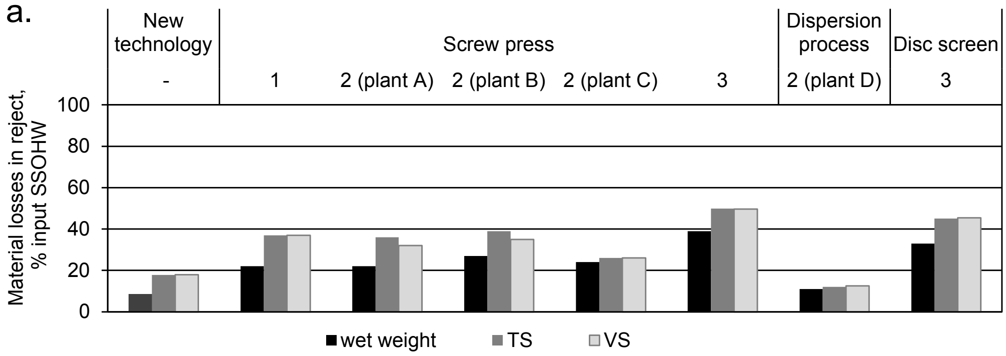
For the main advantages of the new technology versus the existing alternatives the following can be mentioned. Compared to a screw press, SSOHW pre-treatment with the new technology does not require strong pressure to be applied, which helps to decrease non-biodegradable materials in the biomass. Unlike disc screens, where the distribution of input waste between the biomass and the reject is highly dependent on the materials' physical proportions, the distribution of the waste produced by the new technology is more in line with the nature of the material (i.e. if it is biodegradable or non-biodegradable) and thus may also be more efficient. On the other hand, the new technology may be associated with greater water consumption, at least compared to the screw press pre-treatment case presented by Bernstad et al. (2013).

Within the present PhD thesis, a detailed comparison of the new technology to the three pre-treatment alternatives introduced earlier, i.e. a screw press, a disc screen and a dispersion process, was conducted (**Paper II**). The parameters compared were as follows: (1) initial material loss to the reject in terms of wet weight, total solids (TS) and volatile solids (VS), (2) material composition of the reject, including the relative presence of biodegradable materials, (3) biochemical methane potential (BMP) for the biomass after pre-treatment (mL CH_4/g VS biomass), and the total methane output per 1 tonne SSOHW treated (m^3 CH_4/tonne SSOHW), and (4) electricity and water consumption. For data for the new technology, results obtained within the present PhD project were used, while for the screw press, disc screen and the dispersion process, data based on a number of pre-treatment cases available in the literature were considered. The comparison results are presented further in **Figure 1** and **Figure 2**.

As can be seen from **Figure 1 (a)**, the new technology has lower material losses to the reject, based on wet weight, compared to all of the pre-treatment technologies investigated. For material losses to the reject based on TS and VS, the same can be observed when comparing the new technology with the screw press and disc screen pre-treatment cases. Meanwhile, TS and VS losses to the reject with the dispersion process are lower than for the new technology.

The BMP value of the biomass produced with the new technology was in the same range as those reported for the alternative pre-treatment technologies (see **Figure 1 (b)**, BMP). Higher BMP values were expected for those technologies generating more reject per tonne of SSOHW treated, as it was assumed that the VS with the lowest BMP, e.g. paper, would be rejected. Thus, VS remaining in the biomass is of better quality, and the BMP measured per tonne of VS is higher. On the other hand, if the BMP values presented in the figure are seen in relation to the results presented in **Figure 1 (a)**, it follows that this is not always true. BMP is highest for the dispersion process that has the least amount of VS in the reject.

Total methane output (m^3 CH_4/tonne SSOHW) was calculated for each individual technology based on the measured BMP, material lost to the reject and general SSOHW characteristics for TS and VS content (set at 40% and 89% of TS, respectively). The yield from biogas production was assumed to be 70% of the measured BMP. The total methane output per tonne of SSOHW is dependent on both the BMP of the produced biomass and the share of recovered VS. Therefore, a pre-treatment technology with a lower BMP may end up with more total methane produced per tonne of SSOHW than a technology with a higher BMP, albeit with less VS recovered in the biomass. Herein (see **Figure 1 (b)**, total methane output), this can be observed for the new technology compared to a screw press in case 2 (plant B). In other cases, total methane output with the new technology is larger than for other technologies when the BMP of the biomass from the new technology is larger, i.e. compared to a screw press in cases 1 and 3 and the disc screen case.



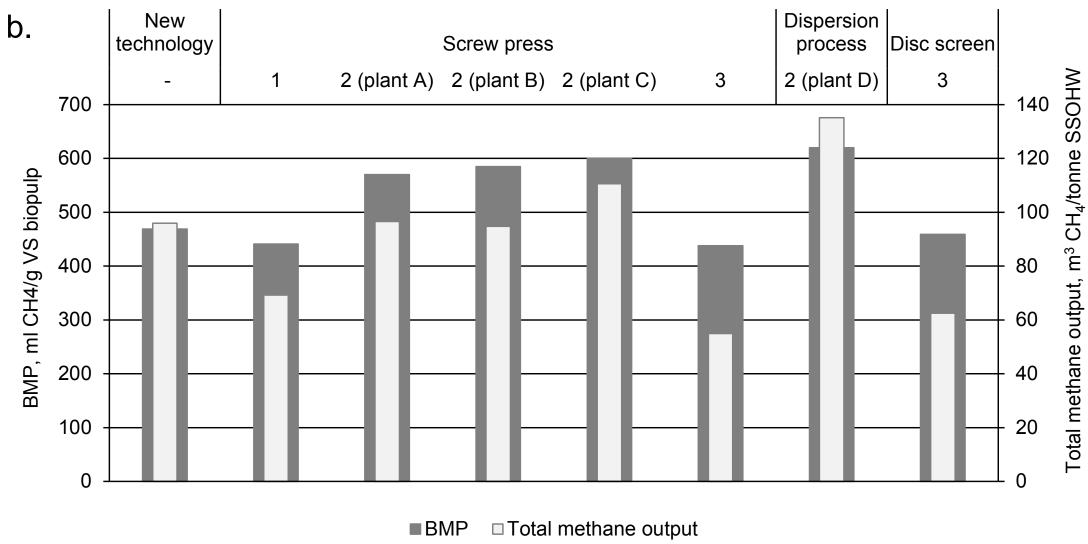


Figure 1. Comparison of the new SSOHW pre-treatment technology with alternatives existing in Scandinavian countries, i.e. a screw press, a disc screen and a dispersion process. Figure 1 (a) shows material losses to the reject, given as a percentage of the input material's wet weight, TS and VS content. Figure 1 (b) shows the biochemical methane potential (BMP) for the biomass after pre-treatment (mL CH_4/g VS biomass) and the total methane output per 1 tonne SSOHW treated (m^3 CH_4/tonne SSOHW). Numerals on the x-axis represent the data source for the pre-treatment alternatives and are as follows: 1 from Eriksson and Holstroem, 2010; 2 from Bernstad et al., 2013; 3 from Hansen et al., 2007a. The figure is from Paper II.

Figure 2 compares the material composition of the reject from the new technology with the reject composition of the screw press and disc screen pre-treatment technologies (based on Hansen et al., 2007a). Reject from the new technology contained much less biodegradable material (16%) in comparison to the rejects produced by the alternative pre-treatment technologies (88% for the screw press and 80% for the disc screen).

The electricity consumption of the new technology (41 kWh per tonne of SSOHW treated) was only half of the consumption of the dispersion process (83.5 kWh per tonne of SSOHW treated). Meanwhile, the electricity consumption of the screw-press based pre-treatment cases was smaller. For water consumption, the new technology was similar to the dispersion process (1.21 and 1.1 m^3 per tonne SSOHW for the new technology and the dispersion process, respectively) and thereby greater than exemplified for the screw press-based pre-treatment (i.e. 0.6 m^3 per tonne SSOHW).

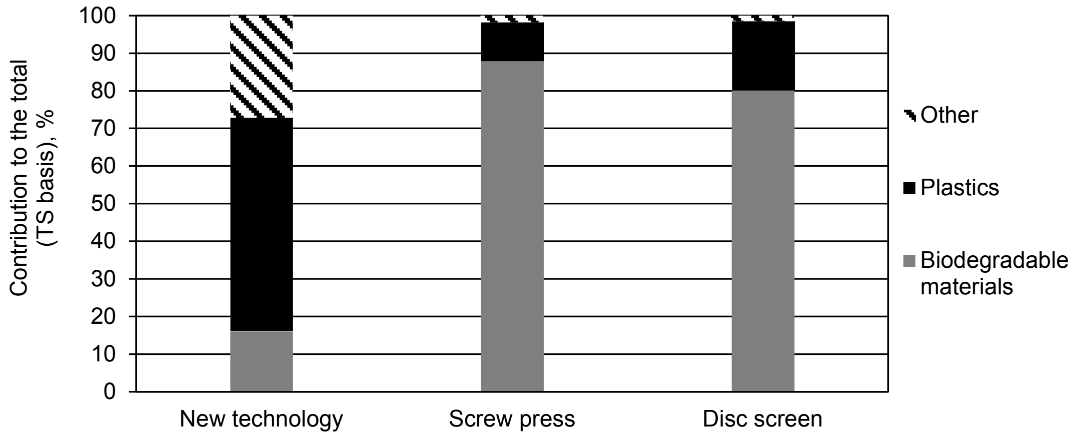


Figure 2. Composition of the reject from the new technology, the screw press and the disc screen; shown as a contribution of biodegradable materials, plastics and other (non-biodegradable materials other than plastics) to total TS in reject. For the screw press and disc screen, data from Hansen et al (2007a) are shown. The figure is adapted from Paper II.

4.4 Data for modelling SSOHW pre-treatment within LCA

To describe SSOHW pre-treatment within LCA, two main data types need to be considered: (1) input material distribution between the pre-treatment outputs – the pre-treated biomass and the reject fraction, (2) resource consumption, e.g. electricity associated with the treatment. The main challenge to modelling the distribution is that concentrations of relevant components (e.g. nutrients, carbon, fibres) are different in different material fractions, and therefore the distributions cannot be fully described by the overall distribution of the material's wet weight, TS and VS. As highlighted in **Paper IV**, the modelling of the pre-treatment depends in practice on the modelling tool and data available, and thus different approaches can be used. Modelling in EASETECH is mass-balance-based and requires transfer coefficients for individual material fractions defined in the input waste composition to be specified (Naroznova et al., 2013). In ORWARE, different waste components like proteins, lipids, etc. are characterised (Carlsson et al., 2015).

Within the present PhD thesis, data for pre-treatment modelling in the EASETECH software were generated for the new pre-treatment technology and also partly for pre-treatment with a screw press (**Paper II**). For the new pre-treatment technology, transfer coefficients for individual material fractions that are commonly distinguished in SSOHW composition were established (**Table 3**). The calculation was based on data for material transfer through the system (wet weight and TS), the fractional composition of the two process outputs (obtained during investigations into the technology, see **section 2.2**) and some external data from the EASETECH model (see details in the corresponding manuscript). Considering these transfer coefficients for the new technology and a similar dataset for a screw press presented earlier in Cowi (2012), transfer coefficients on the substance level were further obtained. In particular, the coefficients for transferring individual material fractions were applied to model SSOHW pre-treatment using the EASETECH software. Three SSOHW composition cases were considered, and estimates for the transfer of carbon (total, biogenic and fossil), nutrients such as nitrogen (N) and phosphorous (P) and heavy metals (Pb, Cd, Cr, Cu, Ni, Zn, Hg) in the two pre-treatment cases were derived (see **Table 4**).

Table 3. Transfer of different material fractions from the untreated SSOHW to the biomass generated by the new pre-treatment technology. The table is from Paper II.

		% total (TS basis)
Non-biodegradable	Hard plastic	0.2
	Soft plastic	0.2
	Other metal	2
	Al foil and containers	4
	Textiles	3
	Clear glass	31
	Other combustibles	11
Biodegradable	Vegetable food waste	95
	Animal food waste	97
	Yard waste. flowers	84
	Paper and cardboard containers	99
	Kitchen towels	99
	Animal excrements and bedding	98
	Diapers	99
	Dirty cardboard	99
	Dirty paper	99

Table 4. Transfer of nutrients (N, P), heavy metals (Pb, Cd, Cr, Cu, Ni, Zn, Hg) and carbon (total, biogenic and fossil) from the untreated SSOHW to the biomass generated by the new pre-treatment technology and a screw press-based pre-treatment technology. Shares (%) of total amounts in untreated SSOHW ± standard deviation. The table is prepared based on the results presented in Paper II.

		New technology	Screw press
Carbon	total	85 ± 6	65 ± 5
	biogenic	91 ± 3	70 ± 2
	fossil	18 ± 10	17 ± 9
Nutrients	N	88 ± 5	77 ± 4
	P	92 ± 2	82 ± 2
Heavy metals	Pb	20 ± 15	16 ± 9
	Cd	75 ± 10	62 ± 6
	Cr	35 ± 19	15 ± 6
	Cu	68 ± 17	28 ± 5
	Ni	76 ± 13	23 ± 3
	Zn	71 ± 12	55 ± 7
	Hg	82 ± 6	67 ± 3

5 The AD of SSOHW from an LCA perspective

5.1 Life cycle stages of the AD of SSOHW

Life cycle stages of the waste management system used to control the AD of SSOHW are the same as for a waste management system with AD in general: (1) AD operation, including energy consumption and methane emissions due to leakages, (2) biogas utilisation followed by energy recovery and (3) utilisation of digestion residue (digestate). When the AD of SSOHW is the main focus, SSOHW pre-treatment prior to AD, followed by reject fraction utilisation, may be differentiated as additional stages in the life cycle. In case consequential LCA is applied, and thereby system expansions are used, marginal production of energy and mineral fertilisers that are avoided will be included.

5.2 Environmental impacts of the AD of SSOHW in previous studies

In previous studies investigating the environmental impacts of the AD of SSOHW, e.g. Bernstad and la Cour Jansen (2011) and Fruergaard and Astrup (2011), the biogas utilisation scheme that can be different depending on national incentives, e.g. vehicle fuel production is dominant in Sweden and combined heat and power (CHP) production is favoured in Denmark, was found to be fundamental to the results for global warming potential (GWP, kg CO_2 eq.). The energy system with respect to the marginal source of electricity was also emphasised as being important. The common conclusion in the two studies was that the GWP-wise use of biogas for CHP might be preferred to using biogas as a vehicle fuel if a CO_2-intensive electricity marginal, e.g. electricity from coal-based CHP, is substituted. Moreover, in the two studies the environmental contribution of digestate utilisation on land was highlighted as being substantial with respect to nutrient enrichment (kg NO_3 eq.).

5.3 Climate change effects associated with SSOHW AD compared to incineration

As evident in the previous LCAs for SSOHW management, e.g. Bernstad and la Cour Jansen (2011) and Fruergaard and Astrup (2011), the climate change effects of the AD of SSOHW compared to incineration are not always better. In general, cases with better incineration performance, shown in the two studies, were accompanied by high energy recovery efficiency for incineration as well as fossil-intensive energy marginals considered for the substitution.

The climate change effects of the AD of SSOHW compared to incineration were also investigated within the present PhD thesis (**Paper III**). The investigation consisted of two parts. In the first part, LCAs for AD and the incineration of individual biodegradable material fractions that can be differentiated in SSOHW composition were conducted and environmental impacts for global warming potential (GWP) evaluated. In the second part of the investigation, the LCAs' results were applied to estimate the GWP involved in treating 1 tonne of SSOHW which may have been retrieved from unsorted municipal solid waste through introducing SSOHW sorting guidelines with the corresponding material fractions included (henceforth referred to as "SSOHW potential"). Ten treatment options representing different cases of the sorting guidelines were considered. Material fractions included in the first part of the investigation were the eight biodegradable material fractions characterised in the present PhD thesis (see **section 3.2.2**). For SSOHW potential, the relative distribution of these material fractions in typical unsorted municipal solid waste in Denmark was considered.

In the LCAs, the life cycle for the AD system consisted of the following: the AD unit, biogas utilisation with a biogas engine followed by marginal energy substitution and digestate use on land, followed by the substitution of mineral nitrogen. The incineration system comprised an incineration unit accompanied by an energy recovery facility, followed by marginal energy substitution and the treatment of bottom and fly ashes, namely landfilling for bottom ashes and neutralisation with basic waste for fly ashes (a detailed description of the neutralisation process can be found in Astrup, 2008). Two different AD cases and four incineration cases were considered. The two AD cases were associated with (1) combined heat and power production (CHP) from biogas and (2) electricity production only. For incineration, four technology cases currently available in Europe were covered: (1) an average incinerator with CHP production, (2) an average incinerator with mainly electricity production, (3) an average incinerator with mainly heat production and (4) a state-of-the art incinerator with CHP working at high energy recovery efficiency levels. In modelling, energy recovery efficiencies corresponding to each case were specified. For further comparison, five scenarios were defined where specific AD and incineration plant cases were compared to each other (see **Table 5**). For the marginal energy framework, conditions representative of Europe as a whole were used – defined as a fuel mix of 72% coal, 19% nu-clear power, 6% oil and 3% natural gas for marginal electricity, and a mix of 76% coal and 24% oil for marginal heat (see details in the corresponding manuscript). To check the robustness of the results for the comparisons, potential changes to AD and incineration technologies, material properties such as biochemical methane potential (BMP) and lower heating value (LHV) and GWP factor of electricity marginal were analysed.

The ten treatment options used for the second part of the investigation were options (I-X) presented in

Table 6 and further described as follow. For treatment option (I), incineration of the entire amount of material was considered. For treatment options (II-IX), the eight material fractions were taken away from incineration one by one (i.e. considered as sorted out through introducing SSOHW sorting guidelines, with the corresponding material fractions included) and were treated by AD instead. For treatment option (IX) the entire amount of material was treated with AD (corresponds to the case of SSOHW sorting guidelines with all eight material fractions included). Treatment option (X) reflected the case where the SSOHW sorting guidelines included only material fractions which in the first part of the investigation were proved to be more attractive for AD than for incineration. An investigation was undertaken, by considering the five scenarios developed within the LCA part of the study (see **Table 5**). Thus, five situations combining specific AD and incineration cases were covered.

The main outcomes of the investigation are described in the two next sections of the present thesis (**section 5.3.1** and **section 5.3.2**).

Table 5. Scenarios for the comparison of specific AD and incineration cases. The table is from Paper III.

	AD plant case	Incineration plant case
A1: district heating is available for both incineration and AD	AD with CHP	Average incinerator with CHP
electric efficiency (net):	*38%*	*15%*
thermal efficiency (net):	*46%*	*37.1%*
A2: no connection to district heating for AD	AD with electricity production only	Average incinerator with CHP
electric efficiency (net):	*42%*	*15%*
thermal efficiency (net):	*-*	*37.1%*
B2: district heating is not available for both incineration and AD	AD with electricity production only	Average incinerator with mainly electricity production
electric efficiency (net):	*42%*	*21.6%*
thermal efficiency (net):	*-*	*4.5%*
C1: incinerator with mainly heat production	AD with CHP	Average incinerator with mainly heat production
electric efficiency (net):	*38%*	*0%*
thermal efficiency (net):	*46%*	*77.2%*
D1: state-of-the art incinerator is built	AD with CHP	State-of-the art incinerator running at high energy recovery efficiencies
electric efficiency (net):	*38%*	*22%*
thermal efficiency (net):	*46%*	*73%*

Table 6 Ten options for treating 1 tonne of SSOHW potential. The table is from Paper III.

No.		Description
I	:	Entire SSOHW potential is incinerated
II	:	AD of animal food waste (AFW) and incineration of the others
III	:	Treatment option II + vegetable food waste (VFW) added to AD
IV	:	Treatment option III + kitchen tissue (KT) added to AD
V	:	Treatment option IV + vegetation waste (VW) added to AD
VI	:	Treatment option V + moulded fibres (MF) added to AD
VII	:	Treatment option VI + animal straw (AS) added to AD
VIII	:	Treatment option VII + dirty paper (DP) added to AD
IX	:	Entire SSOHW potential is treated with AD (Treatment option VIII + dirty cardboard (DC) added to AD)
X	:	AD treatment of material fractions with GWP savings in the AD system larger than in the incineration system and incineration of the others

5.3.1 GWP of treating individual material fractions

The GWPs for treating individual material fractions in the two specific AD and four incineration system cases are presented in **Table 7.** Characterised net results (kg CO_2 eq./kg material wet weight) obtained within the present PhD thesis in relation to **Paper III** are shown. Comparing the results of the five scenarios established within the present PhD thesis (**Table 5**), it was discovered that only one material fraction – vegetable food waste (VFW) – was attractive for AD in all comparison cases. For animal food waste (AFW), kitchen tissue (KT), vegetation waste (VW) and dirty paper (DP), better performance with AD was observed in all cases except for scenario D1 (which compared AD with CHP and the state-of-the art incinerator). For moulded fibres (MF) and dirty cardboard (DC), better performance with AD was observed in scenario C1 only (compared to AD with CHP and incineration with mainly heat production). For animal straw (AS), no better performing case with AD was observed. The results herein were found as being fully robust to a ± 10% change of the reference assumptions for CH_4 loss through leaking from the digesters, a GWP factor of the electricity marginal and electricity recovery efficiency for both AD and incineration. The results were not fully robust when the BMP, LHV or methane yields of the AD plant were changed (both increased and decreased). The non-robust cases, however, were few in number.

It was also noted that in most of the cases the differences in net GWP of a specific AD and incineration case were determined by the total GWP savings achieved in each system. These comprised savings related to energy marginal substitution in the systems with incineration and related to the two energy marginal substitution systems and digestate treatment in the AD systems. In some cases, e.g. scenario D1 with animal food waste (AFW), though, benefits from total GWP savings for AD versus incineration were outweighed by the GWP loads of the former (related to the energy consumption and methane emissions involved in operating the AD unit). The magnitudes of GWP loads and savings were, in the meantime, dependent on the material fraction in focus. In general, the following was noted: GWP savings from energy marginal substitution (both electricity and heat) were greatest for material fractions such as animal food waste (AFW), dirty paper (DP) and dirty cardboard (DC), which could be explained by the fact that the most CH_4 was produced per kg wet weight of these material fractions. For AFW, the result was related to the substantial BMP of this material fraction (572 ml CH_4/g VS), while for DC and DP the large content of total solids (TS) in these fractions (49% wet weight for DP and 71% for DC) was the key. In incineration systems the magnitude of GWP savings from energy marginal substitution was determined by the total energy potentials in each particular material fraction, which, in turn, was dependent on LHV values and of total solids (TS) content. Within the present investigation, total energy potential was the largest for a material fraction such as dirty cardboard (DC) and was basically related to the high TS content (86%) of this material fraction. For animal food waste (AFW), GWP loads determined by the content of N in this material fraction, e.g. N_2O emissions associated with digestate use on land, were highlighted, while for material fractions such as moulded fibres (MF), animal straw (AS), dirty paper (DP) and dirty cardboard (DC), amounts of carbon spread on land in the digestate, and the GWP effects of carbon storage in soil thereto related, were emphasised.

Table 7. GWP of treating individual material fractions in the two specific AD and four incineration system cases. Characterised net results (kg CO_2 eq./kg material wet weight) obtained in Paper III are shown.

	Animal food waste (AFW)	Vegetable food waste (VFW)	Kitchen tissue (KT)	Vegetation waste (VW)	Moulded fibres (MF)	Animal straw (AS)	Dirty paper (DP)	Dirty cardboard (DC)
AD with CHP	-0.47	-0.22	-0.32	-0.14	-0.28	-0.19	-0.50	-0.58
AD with electricity production only	-0.41	-0.19	-0.28	-0.12	-0.25	-0.18	-0.44	-0.52
Average incinerator with CHP	-0.31	-0.11	-0.20	-0.11	-0.33	-0.32	-0.42	-0.61
Average incinerator with mainly electricity production	-0.31	-0.12	-0.20	-0.12	-0.33	-0.32	-0.42	-0.61
Average incinerator with mainly heat production	-0.20	-0.07	-0.13	-0.07	-0.22	-0.21	-0.28	-0.41
State-of-the art incinerator working at high energy recovery efficiencies	-0.51	-0.20	-0.33	-0.20	-0.54	-0.53	-0.70	-1.00

5.3.2 The GWP of treating 1 tonne of SSOHW potential in municipal solid waste

The GWP of treating 1 tonne of SSOHW potential in municipal solid waste (henceforth referred to as "SSOHW potential") was analysed in relation to **Paper III** of the present PhD thesis. As introduced at the beginning of this section (i.e. **section 5.3**), ten treatment options were set-up representing different cases of material allocation for the two treatment options, i.e. AD and incineration. Moreover, two different AD cases and four different incineration cases were differentiated.

In the results, the GWP of incinerating 1 tonne of SSOHW potential ranged from -108 to -279 kg CO_2 eq., with the smallest result (least negative) being for the average incinerator with mainly heat production and the largest result being for the state-of-the art incinerator, while the GWP of treating 1 tonne of SSOHW potential with AD was -273 kg CO_2 eq. for AD with CHP and -238 kg CO_2 eq. for AD with electricity production only. It was also found that the biggest increase in GWP savings that could be achieved by implementing an AD of SSOHW scheme was induced by the AD of the food waste material fractions (animal food waste and vegetable food waste within the investigation). Changes after adding kitchen tissue to AD were also notable, while changes induced by AD treatment of the rest of the material fractions (e.g. vegetation waste, moulded fibres, animal straw, dirty paper and dirty cardboard) were negligible. By only allocating to AD the material fractions individually proven to be attractive for this treatment (based on the LCAs performed in the present study), increases in GWP savings of up to ca. 7% were seen compared to in the case where all possible material fractions in the SSOHW were treated in the same way.

5.4 Climate change effects of optimising the AD of SSOHW at the pre-treatment stage of the life cycle

A need to improve the AD of SSOHW at the pre-treatment stage of the life cycle, in order to minimise losses of biodegradable material and nutrients in the reject fraction, has been recognised (Bernstad et al., 2013). The environmental effects of this issue with regards to global warming potential (GWP) were studied by Carlsson et al. (2015) and Naroznova et al. (2013) and are also addressed in the present PhD thesis (**Paper IV**). Consequential LCA was used in all of the cases, and the GWP effects of the AD of SSOHW, considering different efficiencies in the pre-treatment, were compared. Investigations reported by Carlsson et al. (2015) and Naroznova et al. (2013) were performed as case studies, with a special focus on Swedish and Danish conditions, respectively. In the present PhD thesis, GWP effects for the AD of SSOHW within framework conditions that varied with respect to biogas utilisation and energy system, representing different geographical regions and/or different time frames, were quantified.

The mutual result for all three studies is that there is no big difference in the GWP performance of the AD of SSOHW when changes to pre-treatment efficiency, such as ± 10% material recovered in the biomass, are in focus. GWP effects for the separate life cycle stages, e.g. biogas utilisation and reject utilisation, are more pronounced. Generally, smaller material losses in the pre-treatment reject result in larger amounts of energy and nutrients recovered, and thus larger GWP savings are seen when substituting marginal energy and mineral fertilisers. Meanwhile, a larger reject amount in the case of lower material recovery leads to more savings induced by reject incineration. In this context, assumptions around the marginal source of electricity, methane yield (defined as a share of laboratory BMP that is achieved in full-scale AD operations) and energy recovery efficiency by incineration were highlighted as important factors.

As part of the present PhD thesis' investigation, it was also discovered specifically that the benefits of replacing the CO_2 intensive electricity marginal associated with reject incineration may outweigh GWP savings induced by the AD of SSOHW when biogas is used for vehicle fuel, while material recovery following pre-treatment decreases to 70% (TS basis) or less. Net GWP changes compared to the reference material recovery level were, however, small in all cases. Moreover, an issue regarding pre-treated biomass quality in relation to digestate suitability for land application was addressed. For this matter, two levels of digestate quality, associated with low and high degrees of non-biodegradable contaminants in the pre-treated biomasses, were introduced. Digestate with a high degree of contamination was considered as non-suitable for land application and was used to produce digestate pellets for energy recovery. The LCA results in this regards showed that, GWP-wise, the AD of SSOHW accompanied by energy recovery from digestate, instead of digestate land application, may be beneficial when waste heat from biogas utilisation is used for digestate drying – as required by the pellet production process.

6 Conclusions

6.1 Good practice for the AD of SSOHW

6.1.1 Material fractions to be included in SSOHW sorting guidelines for AD when incineration is the alternative

As shown by the present PhD thesis, not all biodegradable material fractions present in municipal solid waste are attractive options for AD treatment when climate change effects are in focus and incineration is considered as the alternative waste treatment option (the most representative system used by European Union member countries). In this regard, in order to avoid sub-optimising the SSOHW management system with regards to global warming potential (GWP), it might be of importance to design SSOHW sorting guidelines properly, by including only those material fractions whose environmental performance for GWP with AD is better than or an alternative treatment (e.g. incineration). In the present PhD thesis, the set of material fractions determined as attractive for AD depended on the specific incineration case. Only one material fraction – vegetable food waste – was always better for AD compared to incineration. For animal food waste, kitchen tissue, vegetation waste and dirty paper, AD performance was better unless it was compared to a highly efficient incinerator. Material fractions such as moulded fibres and dirty cardboard were attractive for AD only under framework conditions where AD with CHP and incineration aligned mainly with heat production were compared. Finally, animal straw was always better to incinerate. Moreover, it was shown in the present PhD thesis that sorting out biodegradable material fractions, whose total amount in unsorted municipal solid waste is small, for subsequent AD treatment may be less fruitful GWP-wise. For Denmark, SSOHW comprised of food waste (both animal and vegetable derived) and kitchen tissue was generally suggested to be included for organic waste sorting, while the inclusion of material fractions such as vegetation waste, moulded fibres, animal straw, dirty paper and dirty cardboard was of less importance.

6.1.2 Physical pre-treatment within the AD of SSOHW

Physical pre-treatment is an important stage within the AD of SSOHW and its optimisation with regards to the share of biodegradable material losses and the quality of the produced biomass. In the present PhD thesis, a thorough assessment of a new Danish pre-treatment technology was performed, and a comparison with alternative pre-treatment technologies currently existing in

Scandinavian countries, e.g. screw press, disc screen and the dispersion process, was made. According to the results, the biomass produced by the new technology was homogeneous, low in both larger particles and non-biodegradable material content and with sufficient BMP value to be used for AD treatment. In comparison to pre-treatment with a screw press and a disc screen, very little reject was generated, and the content of biodegradables therein was small, which, in turn, suggests better recovery of both energy and nutrients with the new technology. Comparing the new technology with the dispersion process (the one that had a similar share of rejected material), electricity consumption for the new technology was lower and water consumption was in the same range.

Moreover, the climate change effects of optimising the AD of SSOHW at the pre-treatment stage of the life cycle were studied. The main finding was that a change in pre-treatment efficiency, such as ± 10% material recovered in the biomass, does not affect the net global warming potential of the system significantly. In this respect, it may be suggested that other aspects, e.g. economy, practicality or other environmental aspects of relevance, might be used as guidance when selecting the technology for practical use. The effects for the separate life cycle stages of the AD of SSOHW, e.g. biogas utilisation, reject utilisation, were, in the meantime, more pronounced. The issues discovered in this regard, though, were the same as commonly highlighted for energy recovery waste management systems, e.g. the role of the source of marginal energy or the efficiency of the energy recovery technique being considered.

6.2 Future work perspectives

Through the efforts of the present PhD thesis, background data for the environmental assessment of a wide range of AD of SSOHW implementations in Europe were generated, whilst the need for further research into the two following issues was also revealed:

- **Impact assessment for other impact categories**: within the present PhD thesis, only the environmental effects of the AD of SSOHW with respect to global warming potential (GWP) were addressed. Impact assessment with regard to other impact categories, e.g. nutrient enrichment, acidification, may also be relevant, for instance when the effects of pre-treating produced biomass quality are studied. For a comparison of AD and incineration, results in other impact categories may be very different from those attributed to GWP (Naroznova et al., 2013; Fruergaard and Astrup, 2011), and so it is important to determine these through further research on the subject.

- **Social aspect of SSOHW**: along the wide range of AD of SSOHW implementations, a social aspect with regards to waste source separation in practice may be of importance. As stated by Amend et al. (2014), organic waste sorting may become more efficient when citizens are provided with clear, understandable information and simple explanations. With that in mind, it is important to ensure that the material fractions specified for sorting are easy to recognise, and therefore investigations into the behaviour of the sorting participants might be relevant.

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IV Carlsson, M., Naroznova, I., Møller, J., Scheutz, C., Lagerkvist, A. (2015). Importance of food waste pre-treatment efficiency for global warming potential in life cycle assessment of anaerobic digestion systems. Resources, Conservation and Recycling, 102, 58-66. DOI 10.1016/j.resconrec.2015.06.012

In this online version of the thesis, **paper I-IV** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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Water Resources Engineering, Urban Water Engineering,
Residual Resource Engineering and Environmental Chemistry & Microbiology.

The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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